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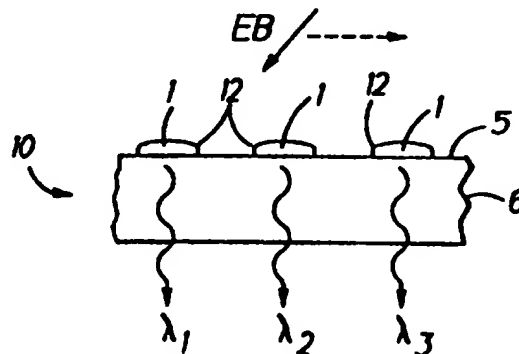
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(54) Title: SEMICONDUCTOR NANOCRYSTAL DISPLAY MATERIALS AND DISPLAY APPARATUS EMPLOYING SAME

(57) Abstract

A class of high efficiency (e.g., > 20 %) materials for use as display pixels (12) to replace conventional phosphors in television, monitor, and flat panel displays (10). The materials are comprised of nanocrystals (1) such as $\text{CdS}_x\text{Se}_{1-x}$, CuCl , GaN , $\text{CdTe}_x\text{S}_{1-x}$, ZnTe , ZnSe , ZnS , or porous Si or Ge alloys which may or may not contain a luminescent center. The nanocrystals (1) may be doped with a luminescent center such as Mn^{2+} or a transition metal. The nanocrystals (1) have passivated surfaces to provide high quantum efficiency. The nanocrystals (1) have all dimensions comparable to the exciton radius (e.g., a size in the range of approximately 1 nm to approximately 10 nm). The invention further teaches a quantum dot nanocrystal display phosphor that has a size selected for shifting an emission wavelength of a constituent semiconductor material from a characteristic wavelength observed in the bulk to a different wavelength. A field effect flat panel display is described that employs the nanocrystals (1) of this invention, as are embodiments of plasma displays and fluorescent light sources.



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5 SEMICONDUCTOR NANOCRYSTAL DISPLAY MATERIALS AND DISPLAY
 APPARATUS EMPLOYING SAME

FIELD OF THE INVENTION:

10 This invention relates generally to materials suitable for
 emitting electromagnetic radiation with visible wavelengths
 when suitably excited, and further relates to display
 apparatus having a display screen that contains such
 materials.

15

BACKGROUND OF THE INVENTION:

 Phosphorescent materials or phosphors have been employed
 for a number of years in the construction of cathode ray
20 tubes having a display screen that is excited by an
 electron beam. When struck by the electron beam the
 phosphor material absorbs energy from the beam and
 subsequently re-emits the energy as electromagnetic
 radiation with wavelengths within the visible range.

25

 Representative U.S. Patents in this general area include
 the following.

 Wainer (4,073,989) discloses a cadmium sulfide phosphor
30 that may be deposited as ultra-fine particles on a glass or
 quartz base.

 DiStefano (4,082,889) discloses a cadmium sulfide (CdS)
 semiconductor material. Both the Wainer '989 and DiStefano
35 '889 patents disclose the combination of CdS and ZnS in at
 least one embodiment. The luminescent layer as practiced
 by DiStefano comprises a polycrystalline thin film 40 of
 semiconductor material forming individual grains 36

oriented with random size, orientation, and configuration. The typical size of each grain 36 ranges from about 1 micron to about 100 microns. The film 40 is conductive in the lateral direction. A thin skin 35 of majority type dopant forms a layer which preferably covers all surfaces, whether they be the film surface 34, a grain boundary 38, or the interface 42 between the film 40 and the substrate 32.

10 Delahoy (4,625,071) discloses cadmium sulfide semiconductor particles in a necklace configuration that range in size from 10 to about 3000 angstroms.

15 Mie (4,081,716) discloses a fluorescent display element having an integrated semiconductor element 3 and a cadmium sulfide fluorescent display element.

20 Ellis (4,559,116), Fraas et al. (3,976,361) and Lee (3,583,788) disclose cadmium sulfide semiconductors and/or graded cadmium sulfide crystals with and without other materials.

In an article entitled "Photochemistry of Semiconductor Colloids. 17. Strong luminescing CdS and CdS-Ag₂S Particles", Ber. Bunsenges Phys. Chem. 91, 88-94 (1987), L. Spanhel, H. Weller, A. Fojtik and A. Henglein, report the preparation of Q-CdS sols which fluoresce with quantum yields said to be close to 100%. Strong fluorescence is said to occur when defect sites, at which radiationless recombination takes place, are blocked.

35 In a paper entitled "Doped Nanocrystals of Semiconductors-A New Class of Luminescent Materials", The 1993 International Conference on Luminescence, TH1B-2, Aug. 9-13, 1993, Univ. of Conn., Storrs, Conn., R. N. Bhargava reports the incorporation of a luminescent center (Mn²⁺) in nanosize (30Å-70Å) particles of ZnS. The nanosize ZnS particles are

said to show an increased energy bandgap due to quantum confinement, which is also said to effect the recombination kinetics of the Mn^{2+} luminescence. The 1.7 millisecond Mn^{2+} decay time in the bulk is reported to be shortened to about
5 3 nanoseconds after several hours of curing with UV radiation (300 nm).

In this regard reference is also made to a publication entitled "Optical Properties of Manganese-Doped
10 Nanocrystals of ZnS", Physical Review Letters, Vol. 72, No. 3, pgs. 416-419, 1/17/94, by R. N. Bhargava and D. Gallagher.

Both of these publications describe a method of doping ZnS
15 nanocrystals with Mn.

SUMMARY OF THE INVENTION

This invention teaches the use of a class of high
20 efficiency (e.g., $\geq 20\%$) materials as pixels to replace conventional phosphors in electrically and optically excited television displays, flat panel displays, and illumination sources in general. The materials are comprised of nanocrystals containing a crystalline
25 semiconductor such as CdS_xSe_{1-x} , CuCl, ZnSe, GaN, $CdTe_xS_{1-x}$, ZnTe, ZnS, or porous Si or Ge alloys which may or may contain a luminescent center. That is, the semiconductor material is comprised of at least one of a Group II-VI semiconductor material, a Group III-V semiconductor
30 material, a Group I-VII semiconductor material, and a Group IV semiconductor material. The nanocrystals may be doped with a luminescent center such as Mn^{2+} or a transition metal. The nanocrystals have passivated surfaces to provide high quantum efficiency.

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In accordance with an aspect of this invention, the nanocrystals have all three dimensions comparable to the

exciton radius within the semiconductor material in order to enhance electron-hole overlap as well as to limit the number of phonon modes available for non-radiative decay.

- 5 The invention further teaches a quantum dot nanocrystal display phosphor that has a size selected for shifting an emission wavelength of a constituent semiconductor material from a characteristic wavelength observed in the bulk to a different wavelength.

10

A flat panel display embodiment is described that employs the nanocrystals of this invention. Also described are embodiments of plasma discharge displays and fluorescent light sources.

15

BRIEF DESCRIPTION OF THE DRAWINGS

- The above set forth and other features of the invention are made more apparent in the ensuing Detailed Description of the Invention when read in conjunction with the attached Drawings, wherein:

20

Fig. 1 is a magnified view showing a plurality of the nanocrystals of this invention;

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Figs. 2-4 are each an enlarged cross-sectional view (not to scale) of a display screen that includes the nanocrystals of Fig. 1;

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Fig. 5 is an enlarged cross-sectional view, not to scale, of a flat panel display that is constructed in accordance with an aspect of this invention;

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Fig. 6 is an enlarged cross-sectional view, not to scale, of a plasma discharge display that is constructed in accordance with an aspect of this invention; and

Fig. 7 is an elevational partially cut-away view, not to scale, of a fluorescent light source that is constructed in accordance with an aspect of this invention.

5

DETAILED DESCRIPTION OF THE INVENTION

As is indicated in the above-referenced Bhargava publications, doped nanocrystals have been studied in powder form and have been found to exhibit radiative lifetimes of the order of several nanoseconds, as opposed to the same bulk materials which exhibit millisecond lifetimes.

Undoped nanocrystal materials such as $\text{CdS}_x\text{Se}_{1-x}$ have exhibited radiative lifetimes of nanoseconds, as would be expected for such direct bandgap materials.

The inventor has realized that the short radiative lifetime in both these systems results directly in a high quantum efficiency and a high saturation level for either optical or electrical excitation applications. The short lifetimes are believed to also result in a million-fold increase in the current required to saturate the luminous output of this material when used as a phosphor in, by example, either a cathode ray tube (CRT) or a Field Emission Flat Panel Display. In other words, the material provides a substantially non-saturable phosphor material when used with conventional electron beam current levels. In addition the short lifetime eliminates persistence problems associated with currently available red phosphors staying "on" for too long a time after an excitation beam has moved to another pixel.

In accordance with this invention a selected semiconductor material, such as $\text{CdS}_x\text{Se}_{1-x}$, CuCl , GaN , $\text{CdTe}_x\text{S}_{1-x}$, ZnTe , ZnSe , ZnS , or porous Si or Ge alloys, which may or may not contain a luminescent center, is reduced, such as by a

mechanical process, to a nanocrystal form. The selected material may instead be precipitated from an organometallic reaction to form the nanocrystals. In accordance with an aspect of this invention the individual nanocrystals are
5 formed or selected so as to have all three dimensions comparable to an expected exciton radius within the selected semiconductor material, where an exciton is considered to be a coupled electron-hole pair. This beneficially enhances electron-hole radiative recombination
10 by increasing the electron-hole overlap and, in addition, the small size allows for a reduction in the number of low energy phonons available for non-radiative decay. Non-radiative decay is undesirable in that it reduces quantum efficiency. By example, the size of the individual
15 nanocrystals can be selected by controlling the nucleation process in the colloid (for example, by controlling the pH), and/or by sedimentation or filtering.

In general, the semiconductor material is comprised of at
20 least one of a Group II-VI semiconductor material, a Group III-V semiconductor material, a Group I-VII semiconductor material, and a Group IV semiconductor material. A typical exciton radius for the semiconductor materials of interest herein results in a nanocrystal having all three dimensions
25 in the range of approximately 1 nm to approximately 10 nm. The value of the exciton radius is a function of the coulomb attraction between the electron and the hole, and the effective masses of the electron and the hole within the crystalline lattice of the semiconductor material.

30 The nanocrystals may next be doped with a luminescent center, such as Mn^{2+} , or a transition metal (elements 21-29, i.e., scandium through copper; elements 39-47, i.e., yttrium through silver; elements 57 through 79, i.e., lanthanum through gold; and elements from 89 (actinium on).
35 The doping may be accomplished by the use of suitable chemical precursors in the wet chemical colloid route to

the preparation of these materials. The selected dopant may be present on the surface of the semiconductor core material, and/or embedded within the crystal lattice of the semiconductor core material. The dopant or luminescent center(s) function as a sink for electrons and/or holes that are generated within the semiconductor core material due the semiconductor core material being excited by an incident electron, typically an electron that originates from an electron source that drives the display. That is, an electron and/or hole that is liberated in the semiconductor core material is used to populate the luminescent center.

The surfaces of the doped nanocrystals are next passivated to eliminate undesirable non-radiative recombination. One suitable passivation process is described by Bhargava et al. Other suitable passivation approaches apply Cd^+ or Ag_2S (see the L. Spanhel et al. article cited previously) to the surfaces of the nanocrystals. In general, a number of suitable passivation materials and techniques can be employed for eliminating or suppressing nanocrystal surface states that result in non-radiative recombination and a consequent reduction in quantum efficiency.

It is noted that the dopant (the luminescent center material) can also be employed to passivate the nanocrystal. By example, if the semiconductor material of the nanocrystal core is comprised of CdS , then ZnSe can be employed both as a luminescent center and also to passivate the surface of the CdS semiconductor nanocrystal.

Referring to Fig. 1, and in accordance with an embodiment of this invention, the result of the foregoing process is the production of nanocrystals 1 each comprised of: a core material 2, such as $\text{CdS}_x\text{Se}_{1-x}$, CuCl , GaN , $\text{CdTe}_x\text{S}_{1-x}$, ZnTe , ZnSe , ZnS , or a porous Si or Ge alloy; a luminescent center 3, such as atoms of Mn^{2+} or a transition metal that is

coupled to the core material for receiving electrons and/or holes therefrom; and a passivated surface 4. Preferably all or at least a significant proportion (e.g., more than 50%) of the nanocrystals 1 have all dimensions comparable to the exciton radius within the semiconductor core material. These dimensions need not be exactly equal to the exciton radius. The dimensions are instead provided so that size quantization effects are observed, as will be described in further detail below.

Furthermore, in some embodiments of the invention the doping of the semiconductor core material with a luminescent center is not required. By example, for certain direct gap binary and tertiary semiconductors the electron/hole recombination at the band-edge results in the generation of wavelengths within the visible spectrum. By example, CdS provides green, CdSe provides red, CdS_{1-x}Se_x provides a wavelength between green and red (depending on the relative concentrations of S and Se), and GaN provides blue. However, for those semiconductors that emit a non-visible wavelength, for example ZnS which emits in the UV, then the doping with a luminescent center, such as Mn²⁺ or a transition metal, provides recombination over a smaller energy gap and the generation of visible light.

Referring to Fig. 2, the nanocrystals 1 are next contacted on to a first major surface 5 of a substrate 6 to form a display screen 10. The substrate 6 is preferably transparent to the wavelengths emitted by the nanocrystals 1 when electrically or optically excited, and may be comprised of glass, quartz, a suitable polymer and/or an electrically conductive transparent substance such as indium-tin-oxide (ITO) or ZnO. By example, the excitation source may be a conventional electron beam (EB) that is scanned across the nanocrystal material in a raster fashion. The nanocrystals 1 are typically localized within regions or pixels 12. Conventional phosphor-type deposition

methods can be employed for contacting the nanocrystals 1 into the surface 5. It is, however, within the scope of this invention to provide a substantially uniform layer or coating 7 of the nanocrystals 1 upon the surface 5, as is illustrated in the display screen 10' of Fig. 3. Suitable thicknesses for the pixels 12 or the coating 7 are in the range of thousands of angstroms to several hundred microns.

Referring to Fig. 4, the nanocrystals 1 may instead be used in a form where they are nucleated directly within the first major surface 5 of the substrate 6. In this embodiment of a display screen 10'' the nanocrystals may be first deposited on the surface 5, as in Fig. 2, and then the substrate 6 is heated to a point that enables the nanocrystals 1 to become entrapped within a region of the substrate 6 that is adjacent to the surface 5. Conventional techniques for forming semiconductor doped glasses may also be employed.

Fig. 5 illustrates a flat panel display embodiment that employs the light emitting nanocrystals of this invention. More specifically, Fig. 5 illustrates a field emission display 20 that directly generates electrons that impinge onto a nanocrystal layer 22. One suitable embodiment for this type of flat panel display is illustrated in an article entitled "Field Emission Technology Promises Low Power Displays", S.A. Weiss, Photonics Spectra, pg. 42, July 1994. A two-dimensional array of cold cathodes or emitters 24 provides a plurality of discrete electron sources. Electrons (e) are accelerated across a vacuum gap 26 defined by spacers 29 under the influence of a bias potential provided from a controller 32 to impinge on the layer 22 that is comprised of the novel nanocrystal light emitters of this invention. The nanocrystal layer 22 is disposed on a surface of a transparent faceplate 28 that includes a transparent conductor 30, such as ITO. The nanocrystal layer 22 may be provided in the form of

discrete "dots", as a substantially continuous layer, or integrally formed within a surface as in Fig. 4. In response to the incident electrons the nanocrystals 22 emit visible radiation that passes through the transparent electrode 30 and faceplate 28 to an observer. An insulating baseplate 34 supports the various structures of the flat panel display 20, which further includes an insulator 36 and a positively biased extraction grid 38.

10 The nanocrystals of this invention are significantly smaller than a typical four to five micrometer size of conventional phosphors, and furthermore can be operated at significantly lower excitation energies. This is due in part to their relatively small size, and to the passivation
15 of their individual surfaces. In addition, an incident electron may result in the formation of less than 10 electron/hole pairs within the semiconductor core region of the nanocrystals of this invention. This contrasts sharply to the possibly hundreds of electron/hole pairs that may be
20 generated within a conventional phosphor.

The nanocrystal phosphor embodiments of this invention may be considered as "quantum dot phosphors", in that they have a size that generally results in size quantization effects.

25 This size quantization is exploited to produce emissions from display phosphors which are shorter in wavelength than those allowed in the bulk material. The shift towards the blue is given roughly by:

30
$$\delta E \sim \hbar^2 / 8a^2 (1/m_e + 1/m_h);$$

where a is the particle (nanocrystal phosphor) radius, m_e is the effective mass of the electron, m_h is the effective
35 mass of the hole, and h is Plank's constant.

In accordance with this teaching CdS quantum dot

nanocrystal phosphors have been produced which emit in a spectrum from approximately 400 nm to approximately 520 nm, for example 450 nm (blue), whereas the bandgap of pure bulk CdS results in an emission at a characteristic wavelength of about 518 nm.

Another CdS quantum dot nanocrystal phosphor was synthesized using Cd⁺ passivation under a controlled pH range of nucleation in a manner similar to that disclosed by L. Spanhel et al. The quantum dot nanocrystal phosphor was found to exhibit high quantum efficiency luminescence which peaked at 620 nm. Since this wavelength is significantly longer than the pure CdS bandgap emission (about 518 nm), it is believed that the observed luminescence is most likely due to radiatively efficient surface states created during the passivation of the nanocrystal phosphor. In accordance with this teaching the luminescence range of wavelengths has also been extended to a band extending from approximately 400 nm to approximately 900 nm, again by control of the pH during nucleation.

It should be realized that other materials and material combinations can be employed to practice this invention that those explicitly described above. Furthermore, other suitable processing techniques may be employed to yield the same end result. Also, combinations of nanocrystals comprised of different semiconductor material and/or dopants can be employed together to provide emissions with different wavelengths. By example, in Fig. 2 one pixel may emit a first wavelength (λ_1), while adjacent pixels emit second and third wavelengths (λ_2 and λ_3).

Furthermore a display or display device may be in the form of a cathode ray tube having one or more electron guns, an electroluminescent display, a flat panel display, or any of a number of embodiments wherein an excitation source (e.g., electrical and/or optical) is provided for exciting the

light emitting nanocrystal display phosphors of this invention to emit light.

In this regard Fig. 6 is an enlarged cross-sectional view, not to scale, of a plasma discharge display device 40 that is constructed in accordance with an aspect of this invention. A transparent faceplate 42 has a layer 44 of the nanocrystals of this invention disposed on a surface thereof. A backplate 46 defines a cavity 48 within which a gas, for example Xenon, is contained. Electrodes 50 and 52 cause the Xe gas to emit electromagnetic radiation at a first wavelength (λ_1), for example 140 nm. This radiation is absorbed in the nanocrystal phosphor layer 44 and optically excites same to emit electromagnetic radiation at a second, visible wavelength (λ_2).

Fig. 7 is an elevational partially cut-away view, not to scale, of a fluorescent light source 60 that is constructed in accordance with an aspect of this invention. A transparent, generally cylindrical envelope 62 is sealed by two endcaps 64 and 66 having electrodes 68 and 70, respectively. The envelope 62 contains a gas 72, for example mercury vapor, and has a nanocrystal phosphor layer 74 disposed on an inner surface thereof. Electrodes 68 and 70 cause the mercury vapor to emit electromagnetic radiation at a first wavelength (λ_1), for example 246 nm. This radiation is absorbed in the nanocrystal phosphor layer 74 and optically excites same to emit electromagnetic radiation within a band of visible wavelengths generally designated (λ_2). Due to the high efficiencies that are a characteristic of the nanocrystal phosphors of this invention, an increase in both electrical and optical efficiency is made possible.

The gases used in the previous two embodiments are exemplary. That is, other embodiments of this invention may use other gases such as argon and deuterium. As such, gases

that emit in the UV spectrum are preferred for optically exciting the nanocrystal phosphors of this invention when constructing a source of electromagnetic radiation, such as a plasma display and a fluorescent light.

5

It should thus be understood that while the invention has been particularly shown and described with respect to preferred embodiments thereof, it will be understood by those skilled in the art that changes in form and details
10 may be made therein without departing from the scope and spirit of the invention.

CLAIMS

What is claimed is:

1. A display phosphor, comprising:

a core comprised of a semiconductor material; and

a passivated surface region; wherein

said nanocrystal has all dimensions comparable in size to a radius of an exciton within said semiconductor material.
2. A display phosphor as set forth in claim 1 and further comprising a luminescent center that is coupled to said core.
3. A display phosphor as set forth in claim 1 wherein said semiconductor material is comprised of at least one of a Group II-VI semiconductor material, a Group III-V semiconductor material, a Group I-VII semiconductor material, and a Group IV semiconductor material.
4. A display phosphor as set forth in claim 2 wherein said luminescent center is comprised of an ion or a transition metal.
5. A display phosphor as set forth in claim 4 wherein said ion is Mn^{2+} .
6. A display screen, comprising:

a substrate having a first major surface and a second major surface opposite the first major surface; and

a plurality of light emitting nanocrystals disposed

upon said first major surface, individual ones of said plurality of nanocrystals comprising,

a core comprised of a semiconductor material; and

a passivated surface region; wherein

a significant proportion of said plurality of nanocrystals have all dimensions comparable in size to a radius of an exciton within said semiconductor material.

7. A display screen as set forth in claim 6 wherein said plurality of nanocrystals further include a luminescent center that is coupled to said core.

8. A display screen as set forth in claim 7 wherein said semiconductor material is comprised of at least one of a Group II-VI semiconductor material, a Group III-V semiconductor material, a Group I-VII semiconductor material, and a Group IV semiconductor material; and wherein said luminescent center is comprised of an ion or a transition metal.

9. A display screen, comprising:

a substrate having a first major surface and a second major surface opposite the first major surface; and

a plurality of light emitting nanocrystals disposed within a region of said substrate that is adjacent to said first major surface, individual ones of said plurality of nanocrystals comprising,

a core comprised of a semiconductor material; and

a passivated surface region; wherein

a significant proportion of said plurality of nanocrystals have all dimensions comparable in size to a radius of an exciton within said semiconductor material.

10. A display screen as set forth in claim 9 wherein said plurality of nanocrystals further include a luminescent center that is coupled to said core.

11. A display screen as set forth in claim 10 wherein said semiconductor material is comprised of at least one of a Group II-VI semiconductor material, a Group III-V semiconductor material, a Group I-VII semiconductor material, and a Group IV semiconductor material; and wherein said luminescent center is comprised of an ion or a transition metal.

12. A flat panel display, comprising:

a two-dimensional array of electron emitters;

a transparent electrically conductive electrode;

a plurality of light emitting nanocrystals disposed adjacent to a surface of said electrode;

means defining a vacuum space interposed between said two-dimensional array of electron emitters and said plurality of light emitting nanocrystals; and

means for establishing an electric field across said vacuum space between said two-dimensional array of electron emitters and said transparent electrode for accelerating emitted electrons to impinge on said plurality of light emitting nanocrystals; wherein

individual ones of said plurality of light-emitting

17

nanocrystals comprise,

a core comprised of a semiconductor material; and

a passivated surface region; wherein

a significant proportion of said plurality of nanocrystals have all dimensions comparable in size to a radius of an exciton within said semiconductor material.

13. A flat panel display as set forth in claim 12 wherein said plurality of nanocrystals further include a luminescent center that is coupled to said core.

14. A flat panel display as set forth in claim 13 wherein said semiconductor material is comprised of at least one of a Group II-VI semiconductor material, a Group III-V semiconductor material, a Group I-VII semiconductor material, and a Group IV semiconductor material; and wherein said luminescent center is comprised of an ion or a transition metal.

15. A display, comprising:

a display screen comprising a substrate having a surface, said display screen further comprising a plurality of light emitting nanocrystals disposed upon or within the surface, individual ones of said plurality of nanocrystals comprising,

a core comprised of a semiconductor material; and

a passivated surface region; wherein

a significant proportion of said plurality of nanocrystals have all dimensions comparable in size to

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a radius of an exciton within said semiconductor material;

said display further comprising an electron beam source for controllably directing an electron beam onto said plurality of light emitting nanocrystals for causing an emission of light from said plurality of light emitting nanocrystals.

16. A display as set forth in claim 15 wherein said plurality of nanocrystals further include a luminescent center that is coupled to said core.

17. A display as set forth in claim 16 wherein said semiconductor material is comprised of at least one of a Group II-VI semiconductor material, a Group III-V semiconductor material, a Group I-VII semiconductor material, and a Group IV semiconductor material; and wherein said luminescent center is comprised of an ion or a transition metal.

18. A display, comprising:

a display screen comprising a substrate having a surface, said display screen further comprising a plurality of light emitting quantum dot nanocrystals disposed upon or within the surface, individual ones of said plurality of nanocrystals comprising,

a core comprised of a semiconductor material, said semiconductor material having at least one characteristic emission wavelength; and

a passivated surface region; wherein

a significant proportion of said plurality of said quantum dot nanocrystals have a size selected for

shifting an emission wavelength of said semiconductor material from said at least one characteristic wavelength to a different wavelength;

said display further comprising an electron source that provides electrons for exciting said plurality of light emitting quantum dot nanocrystals for causing an emission of light from said plurality of light emitting quantum dot nanocrystals at the different wavelength.

19. A light emitting quantum dot nanocrystal display phosphor, comprising:

a core comprised of a semiconductor material, said semiconductor material having at least one characteristic emission wavelength; and

a passivated surface region; wherein

said quantum dot nanocrystal display phosphor has a size selected for shifting an emission wavelength of said semiconductor material from said at least one characteristic wavelength to a different wavelength.

20. A source of electromagnetic radiation, comprising:

a chamber that contains a gas and that has at least one transparent surface and a plurality of light emitting nanocrystals disposed upon or within the surface, individual ones of said plurality of light emitting nanocrystals comprising,

a core comprised of a semiconductor material; and

a passivated surface region; wherein

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a significant proportion of said plurality of nanocrystals have all dimensions comparable in size to a radius of an exciton within said semiconductor material;

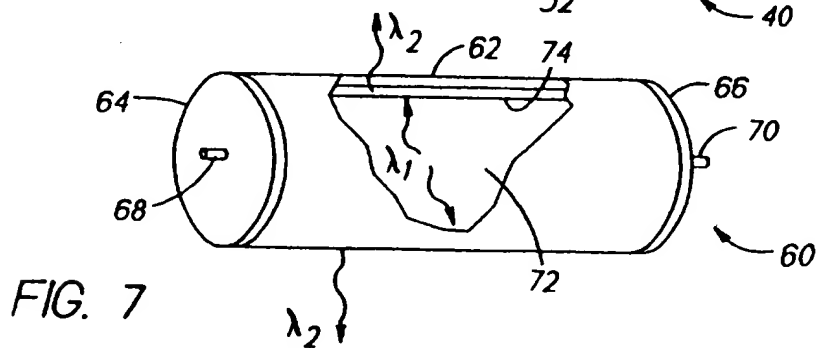
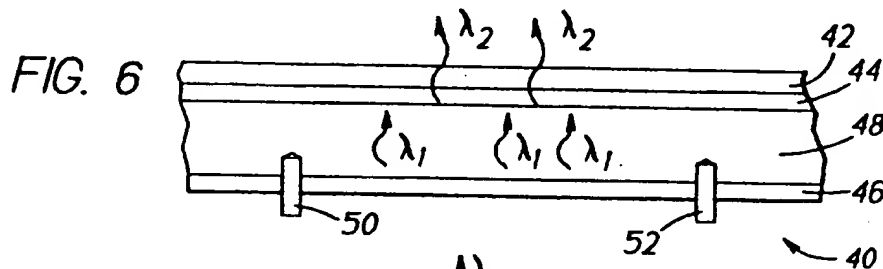
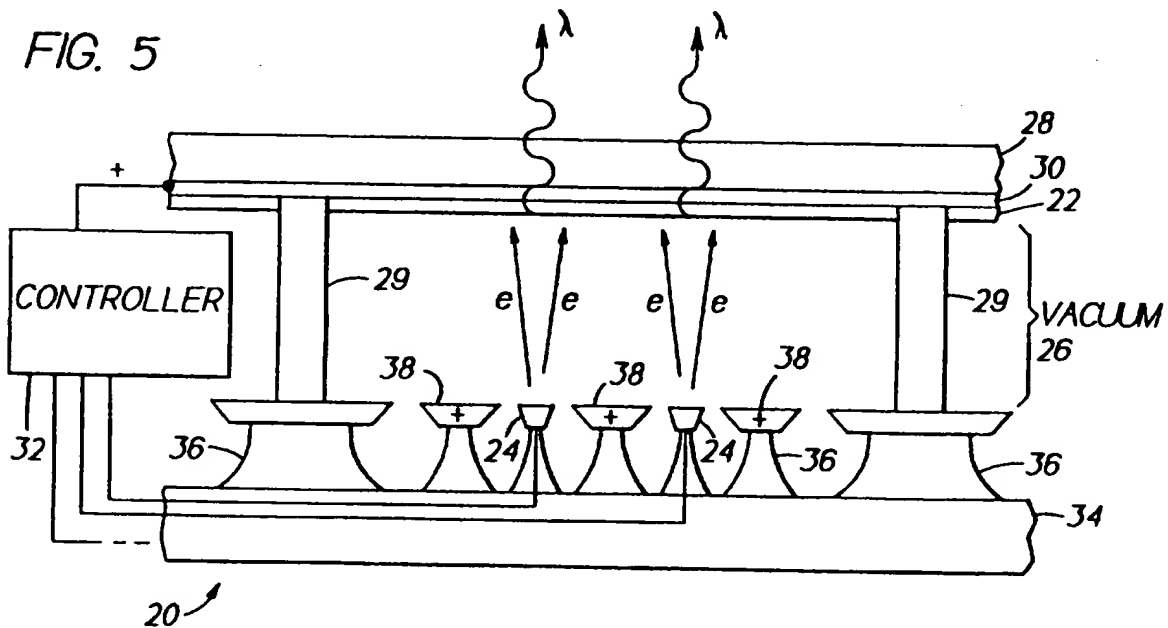
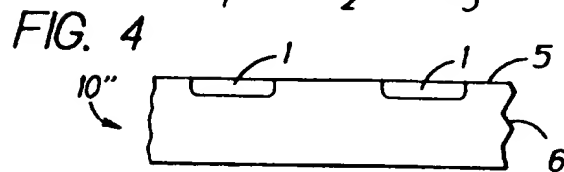
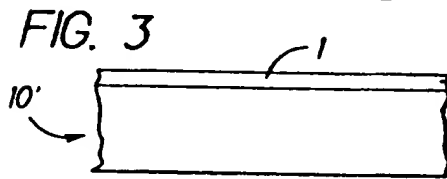
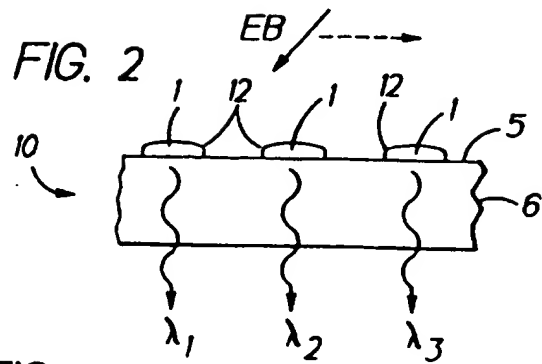
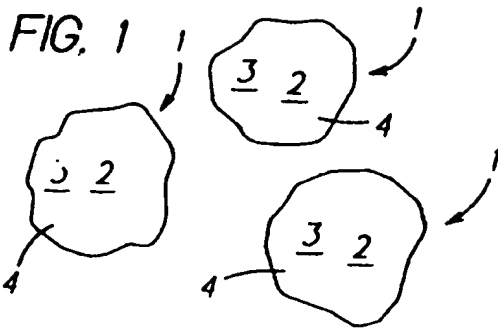
said source of electromagnetic radiation further comprising electrode means for stimulating said gas to emit electromagnetic radiation having a first wavelength that in turn causes said plurality of light emitting nanocrystals to emit electromagnetic radiation having at least one second wavelength.

21. A source of electromagnetic radiation as set forth in claim 20 wherein said plurality of nanocrystals further include a luminescent center that is coupled to said core.

22. A source of electromagnetic radiation as set forth in claim 21 wherein said semiconductor material is comprised of at least one of a Group II-VI semiconductor material, a Group III-V semiconductor material, a Group I-VII semiconductor material, and a Group IV semiconductor material; and wherein said luminescent center is comprised of an ion or a transition metal.

23. A source of electromagnetic radiation as set forth in claim 20 wherein said gas emits electromagnetic radiation within the ultraviolet spectrum.

24. A source of electromagnetic radiation as set forth in claim 20 wherein said gas is comprised of one or more of Hg, Xe, Ar and deuterium.



INTERNATIONAL SEARCH REPORT

International application No.
PCT/US95/13160

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :B32B 9/00, 19/00

US CL :428/688

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 428/403, 688, 690, 917; 250/361 R, 488.1

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y,P	US, A, 5,422,489 (BHARGAVA) 06 June 1995, see entire document.	1-24
Y, P	US, A, 5,446,286 (BHARGAVA) 29 August 1995, see entire document.	1-24
Y, P	US, A, 5,455,489 (BHARGAVA) 03 October 1995, see entire document.	1-24

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:	*T	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
A document defining the general state of the art which is not considered to be of particular relevance	*X*	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
E earlier document published on or after the international filing date	*Y*	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
L document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	*G*	document member of the same patent family
O document referring to an oral disclosure, use, exhibition or other means		
P document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search

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Date of mailing of the international search report

31 JANUARY 1996

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